

REPORT DOCUMENTATION PAGE

AFRL-SR-BL-TR-99

38

Aonic reporting burden for the collection of information is estimated to average 1 hour per record gathering and maintaining the data needed, and certifying and reviewing the collection of information, including suggestions for reducing the burden. To Washington Headquarters Services, Suite 1204, Arlington, VA 22202-3802, and to the Office of Management and Budget, Code 0125, Washington, DC 20503.

1. AGENCY USE ONLY (Leave Blank)

2. REPORT DATE

31 August 1998

3. REPORT TYPE AND UNCLASSIFIED

Final Technical, 1 July 1995 - 31 May 1998

0022

DATA SOURCE
SOURCE OF INFO
1215 JEFFERSON

4. TITLE AND SUBTITLE

Dual-Use Smart Antenna Processing: Blind Adaptive Beamforming, GPS, and Vector Sensors

5. FUNDING NUMBERS

F49620-95-1-0451

6. AUTHOR(S)

Dr. Michael D. Zoltowski

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Purdue University, W. Lafayette, IN 47907

8. PERFORMING ORGANIZATION REPORT NUMBER

Purdue TR-EE-98-17

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Air Force Office of Scientific Research
110 Duncan Avenue, Suite B115
Bolling AFB, DC 20332

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Distribution Unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

There were numerous accomplishments in three areas: blind adaptive beamforming, adaptive null steering for GPS, and vector sensor processing. In the area of blind adaptive beamforming, an algorithm was developed for estimating the respective carrier and timing offset of each of a number of co-channel digital communication signals with linear modulation, along with an SINR maximizing beamforming weight vector for each source. In support of anti-jam protection for GPS, an algorithm was developed for canceling jammers AFTER de-spreading the GPS signal from a given satellite. This approach diminishes the data rate provided to the processor that adapts the beamforming, thereby allowing the use of a low-cost microprocessor. This also facilitates the use of the narrowband blind adaptive beamformer described above to cancel jammers. The algorithm was successfully demonstrated with experimental data from a prototype antenna array. The major development in the area of vector sensors was a closed-form algorithm for unambiguous estimation of the azimuth and elevation angle of each of a number of co-channel sources using a small array of vector sensors with large inter-vector sensor spacings for space diversity to combat fading. As listed in Section 3, this research has been extensively published in journals and presented at a number of high-profile conferences on signal processing and communications. This research has also been honored with a best paper award by Raytheon/E-Systems and a best dissertation award. Transitions of this research to Wright Laboratories at Wright-Patterson Air Force base is in progress.

14. SUBJECT TERMS

vector sensors, smart antennas,
anti-jam spatial filter,
space-time processing, adaptive beamforming

15. NUMBER OF PAGES

21

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT

UNCLASSIFIED

18. SECURITY CLASSIFICATION OF THIS PAGE

UNCLASSIFIED

19. SECURITY CLASSIFICATION OF ABSTRACT

UNCLASSIFIED

20. LIMITATION OF ABSTRACT

UL

**Dual-Use Smart Antenna Processing:
Blind Adaptive Beamforming, GPS,
and Vector Sensors**

**Final Technical Report
Air Force Office of Scientific Research**

Grant/Contract Number: F49620-95-1-0451
Period Covered: 1 July 1995 - 31 May 1998

Principal Investigator:

Michael D. Zoltowski

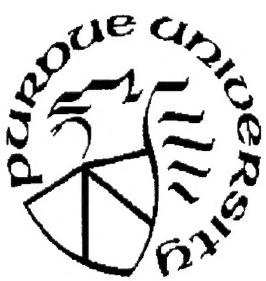
School of Electrical Engineering
1285 Electrical Engineering Building
Purdue University
West Lafayette, IN 47907 USA
e-mail: mikedz@ecn.purdue.edu
Phone: 765-494-3512
FAX: 765-494-0880

Program Director:

Jon A. Sjogren

AFOSR/NM
110 Duncan Ave., Suite B115
Bolling Air Force Base
Washington, DC 20332
jon.sjogren@afosr.af.mil
Phone: 202-767-4940
FAX: 202-404-7496

19990128 040



1 ACCOMPLISHMENTS: EXECUTIVE SUMMARY OF RESEARCH

The original proposal involved research in three technology areas: blind adaptive beamforming, adaptive null steering for GPS, and vector sensor processing. There were substantial numerous accomplishments achieved in each of these three areas, although the research done in the area of adaptive null steering for GPS is primarily reported in the progress report for the New World Vista Topic 20 grant on *Jam-Proof Area Deniable Propagation*. In the area of blind adaptive beamforming, we developed an algorithm for estimating the respective carrier offset of each of a number of co-channel digital communication signals with linear modulation. The algorithm also provides an SINR maximizing beamforming weight vector for each source, as well as the carrier offset for each source. In the area of vector sensors, we have made a number of contributions. First, we developed a closed-form underwater acoustic direction-finding scheme for use in conjunction with an arbitrarily spaced array of vector-hydrophones at unknown locations. Second, we developed an ESPRIT based algorithm for near-field and/or far-field azimuth & elevation angle estimation for use in conjunction with a single vector sensors. Third, we developed a novel MUSIC-based (MULTiple SIgnal Classification) blind source localization algorithm applicable to three-dimensional arbitrarily spaced arrays of velocity-hydrophone triads. These contributions are briefly expanded upon in the following sections.

1.1 Blind Adaptive Beamforming

1.1.1 Source Separation for Narrowband Linear Modulation

The problem solved is that of narrowband digital cellular communications in the presence of multipath and co-channel interferers having the same symbol rate and same overall signal characteristics as the desired source. This describes the interference scenario in an urban commercial cellular environment and arises in military scenarios with “smart” jamming. For a given signal source, an algorithm has been developed for blindly estimating the weight vector yielding the optimum SINR (Signal to Interference Noise Ratio) at the beamformer output. By “blind” we mean that the algorithm does not need to know the angular location of the desired source nor does it need a training sequence.

The ability to blindly estimate the optimum beamforming weight vector is achieved by exploiting the following KNOWN features common to the desired source and the interferers: (i) the symbol rate, (ii) the symbol pulse waveform, and (iii) the signal constellation (finite alphabet, not constant modulus as that negates high bandwidth efficiency.) The instrumental quantity is the Fourier Transform of the expected value of the zero-lag autocorrelation matrix for one symbol period. The scheme employs the PRO-ESPRIT algorithm (developed previously by the PI) to exploit the relationship between the timing offset and optimum beamforming weight vector for each source and the principal generalized eigenvalues and eigenvectors of the matrix pencil formed by evaluating this instrumental quantity at DC and the symbol rate. Extensive simulations have been conducted revealing the algorithm to be rapidly converging, in roughly 20 symbol times or less, and yielding an improvement of many dB's over competing methods such as the subspace-constrained Phase-SCORE algorithm. The rapid convergence is important due to the high variability of the multipath environment.

The algorithm also provides the relative timing offset of each source which is vital for decoding in a narrowband channel using Nyquist waveforms. Extensive simulations have been conducted verifying

the efficacy of the algorithm. A typical simulation result is plotted in Figures 1 and 2. These simulations reveal that the algorithm rapidly converges to the weight vector yielding the maximum SINR, much faster than algorithms premised on the cyclostationarity or constant modulus properties of the digital signals. Note that for high bandwidth efficiency in a narrowband setting, higher order signal constellations are required negating the utility of constant modulus algorithms.

1.1.2 Source Separation with Carrier Offset

Separation of co-channel narrowband digital signals is an important problem that is of intense current interest. Several ways of solving this problem either with multiple antennas or oversampling or both have been proposed recently in the literature. An important practical corollary to the problem statement and the data model used in these is the fact that the carriers of the different users are only nominally the same but in practice have small differences or offsets. The received signal is actually a sum of digital signals modulated by slightly different sinusoids. The receiver demodulates the band-pass signal using a nominal carrier. If there is only one message bearing signal, traditional methods of estimating the carrier offset may be used to estimate the carrier to a satisfactory accuracy and demodulate this signal, converting it to the baseband for further processing and detection. However, when multiple signals are present their carriers will differ, in general, due to independent oscillators, independent offsets and Doppler shifts.

The output of a traditional demodulation scheme would leave residual modulations causing the respective signal constellations for each source to slowly rotate from symbol to symbol. The rotation rates and directions would be different for different users. A typical value for the frequency offset of a crystal oscillator is a few parts per million which corresponds to a few hundred Hertz for carrier frequencies on the order of a 1 GHz. At a baud rate of a few thousand symbols per sec., for example, this leads to a constellation rotation of about fifteen or so degrees per symbol. These rotations pejoratively affect co-channel source separation procedures, in addition to pejoratively affecting the decoding process for each source individually. Co-channel signal separation schemes need to take this phenomenon of imperfect carrier recovery into account or have dubious practical value.

We have developed a scheme for estimating the respective carrier offset of each of a number of co-channel digital communication signals with linear modulation. The scheme requires oversampling of the baseband signals from multiple antenna outputs. The algorithm provides an SINR maximizing beamforming weight vector for each source, as well as the carrier offset for each source. The algorithm is based on cyclic correlation and a variation of ESPRIT similar to that developed during the first year of the grant for recovering symbol timing for each of a number of co-channel digital communication signals.

1.1.3 Exploitation of Finite Alphabet with Carrier Offset

The method described above for dealing with imperfect carrier recovery in the co-channel signal separation problem works well for well-separated constellation rotation rates. However, the performance deteriorates when different users have nearly equal phase rotation rates. The explanation for this is that decreasing the difference in the respective rotation rates for each of two users decreases the angular separation between the two associated ESPRIT eigenvalues. This has the effect of increas-

ing the variance of the associated eigenvector estimates, as determined through classical perturbation analysis. This pejoratively affects the source separation process so that significant amounts of residual co-channel interference corrupt the respective estimates of the two users' corresponding source signals.

In the limiting case where the two phase rotation rates are equal, the eigenvectors computed in the algorithm would not be the correct beamforming weight vectors for effecting source separation even if there were no noise and one employed the asymptotic forms of the autocorrelations and cross-correlations; in this case, each of the two eigenvectors computed in the algorithm would be a (unknown) linear combination of the "true" eigenvectors needed for successful source separation. Yet, in this ideal case, the repeated eigenvalue would yield the common carrier offset for each of the two sources. The effect of the common carrier offset could thus be subsequently eliminated by multiplying the composite sum signal at each antenna by a complex sinusoid at the carrier offset frequency prior to source separation. Source separation could then be effected by any of the aforementioned blind separation procedures which assume no carrier offset, e.g., the ILSP algorithm developed by Talwar, Viberg, and Paulraj.

To solve this problem, we developed an adaptation of ILSP that accommodates carrier offset through additional steps whereby the carrier offset for each co-channel source is updated at each iteration of ILSP. In this mode of operation, our new algorithm provides initial estimates of each co-channel source's individual signal and carrier offset for ILSP, thereby giving the modified version of ILSP (incorporating carrier offset) a good starting point to accelerate convergence.

That is, our new cyclic correlation and ESPRIT based algorithm for estimating the carrier offset and source separating beamforming weight vectors is only used to get the modified version of ILSP going. A nice feature of the modified version of ILSP incorporating carrier offset is that it does not require the symbols for a given user to be i.i.d., nor does it require averaging over enough symbols to reduce the time-averaged cross-correlation between distinct users to near zero.

1.1.4 Extended Kalman Filter Approach to Source Separation with Carrier Offset

When carrier offsets are present and their values are substantial (few hundred Hertz with symbol rates on the order of tens of thousands of symbols per second), the estimation of spatial signatures can no longer be made with a static model. The effect of carrier offsets needs to be built into the model at the very first stage. To this end, we have formulated the evolution of spatial signatures with carrier offsets as a state space problem with unknown parameters to be evaluated by the observer. We have demonstrated that the Extended Kalman Filter (EKF) approach can adequately take care of this under judicious initialization and appropriate linearization and projection of the adaptation of unknown parameters. It is to be noted that this method is not blind and requires a short training sequence to be incorporated into each of the users symbol streams. This enhances the robustness and reliability of the method.

The Extended Kalman Filter and Decision Directed algorithm provide a way of separating multiple co-channel signals received by an antenna array when the demodulation is imperfect. The design parameters in the method mentioned above are the initial estimate of the covariance of the innovations, *i.e.*, α , and the number of training symbols N_{tr} and the total symbols per packet N . Together they determine the reliability, error rates, largest trackable carrier offset, convergence speed and transmis-

sion capacity of the wireless system. In a wireless system, the channel changes slowly with time and has to be re-estimated periodically with every packet.

1.2 Advanced Adaptive Null Steering Concepts for GPS

1.2.1 Coodinate Descent Power Minimization Based Null Steering

What's currently done in one form or another in all operational or experimental adaptive null steering arrays for GPS is a variation on power minimization. The power minimization approach is premised on the fact that the GPS signals are below the noise floor and that the respective signals from different GPS satellites may be selected based on their corresponding PN sequences AFTER beamforming, and may thus pass through the beamformer simultaneously. Constraining the weight on the reference element to be unity, the idea is to find the weights on the auxiliary elements that minimize the power at the beamformer output. Because the GPS signals are below the noise floor, the resulting set of weights effects point nulls in the directions of the interfering sources. What varies from system to system is the algorithm for adaptive the weights to achieve this condition.

The research challenge was to design an algorithm commensurate with an existent prototype hardware configuration developed by E-Systems called the AE-1 CRPA array. In the AE-1 CRPA array the only quantity to drive the algorithm is the output power obtained with a given set of aux weights. That is, not only is there not an A/D converter behind each antenna, there isn't even an A/D after the beam is formed – just a power meter. This runs contrary to the needs of the correlation matrix based array signal processing algorithms developed over the past two decade which assume complex baseband demodulation followed by an A/D for each antenna output.

To facilitate correlation matrix based processing, we developed a strategy for constructing the complex-valued spatial correlation matrix, of dimension equal to the number of antennas, based on the output powers obtained from each of a number of judiciously designed analog beams formed sequentially. In the most general case, we have to form roughly N^2 beams to construct the $N \times N$ Hermitian correlation matrix. However, if the array geometry exhibits symmetries, this number can be reduced by at least a factor of 2. For example, for certain symmetrical array geometries our previous research tells us that we can work with only the real part of a beamspace spatial correlation matrix formed from conjugate symmetric beams. This leads to a performance improvement as well as an attendant computational reduction. Applied here this also saves time as it precludes having to do any power measurements to determine the imaginary parts of the off-diagonal correlation matrix elements – hence, the factor of two reduction in the number of power measurements.

Once the spatial correlation matrix is available, any of the matrix-based array signal processing algorithms may be employed in attempting to cancel the jammers in the GPS band. Note that the AE-1 CRPA prototype antenna array developed by E-Systems, with whom I am worked closely with to effect a transition (see Section 7), is a six element circular (ring) array with an additional element at the center of the circle serving as the reference element. Since it is not necessary to localize the jammers in order to cancel them, we took an approach that was much more amenable to real-time implementation with current off-the-shelf technology, and more robust to array imperfections as well. The algorithm is primarily based on a conjugate gradient search with optimal step size. Discounting the time it takes to load a weight, for the seven element AE-1 CRPA prototype mentioned previously, we can meet the

military specs on jammer cancellation specified by the GPS JPO office in roughly a half a millisecond. This is at least as fast as much higher priced systems which do the complex baseband conversion and 20 MHz A/D conversion behind each antenna element. And the performance is better in the former case as the latter systems only provide four bits per sample due to the very high sampling rate.

1.2.2 Cyclostationarity Based Null Steering After Despread

An algorithm was developed for canceling jammers AFTER de-spreading the GPS signal from a given satellite (based on the code for that satellite). This approach diminishes the data rate provided to the processor that adapts the beamforming, thereby allowing the use of a low-cost microprocessor. This also facilitates the use of the narrowband blind adaptive beamforming algorithm reported in Section 1.1.1. The efficacy of the algorithm was assessed with experimental data from a prototype circular antenna array.

The experimental prototype antenna array consists of 6 elements equi-spaced along a circular perimeter with radius equal to half the wavelength associated with the GPS center frequency of 1.575 GHz. The antenna elements are low cost stacked patch antennas. This configuration provides a wider bandwidth that allows the reception of two services simultaneously: GPS and INMARSAT. To achieve circular polarization, a 90 deg. hybrid is placed below each element antenna, followed by six Low Noise Amplifiers (LNA's) in MMIC technology.

Figures 3 through 6 present the results of an experiment conducted in which the PN code was programmed to receive a GPS signal arriving at an elevation angle of 30 degrees with respect to the boresite axis of the array. After despread, the SNR of the GPS signal was roughly 10 dB per element. In addition, interference was intentionally injected by a nearby radiating antenna at an angle of 20 degrees with respect to boresite, and at a power level 40 dB above the desired GPS signal (prior to despread.) After despread, the aforementioned new narrowband blind adaptive beamforming algorithm was applied. The effectiveness of the interference cancellation scheme was assessed in several different ways. For example, the eye diagram of the antenna with the best SNR was compared with the eye diagram after beamforming. As shown in Figure 6, the eye pattern in the former is not discernible while in the latter it is very clearly defined.

Further research progress in the area of adaptive null steering for GPS is reported in the progress report for the New World Vista Topic 20 grant on Jam-Proof Area Deniable Propagation.

1.3 Extended Aperture Vector Sensor Arrays

The concept is the same as that discussed in the original proposal. A vector sensor consists of six antennas co-located in space that allow one to measure all three components of the electric field and all three components of the magnetic field of an incident wavefield. One vector sensor produces a 6×1 vector at each snapshot. For a given source, the 6×1 subarray manifold is referred to as the E-H manifold since the top 3×1 subvector is the electric field vector for that source, while the bottom 3×1 subvector is the corresponding magnetic field vector. The vector cross product between the top and bottom 3×1 subvectors of the 6×1 E-H manifold for a source is the Poynting vector which yields the radial direction of a source.

1.3.1 Novel Processing of Three Vector Sensors

Consider a system (array) of three vector sensors forming a right triangle. The new algorithm is based on viewing any two pair of vector sensors as an ESPRIT geometry: two identical 6 element subarrays that are displaced in space. The idea is to have the two vector sensors along either leg spaced much greater than a half-wavelength to achieve high accuracy in the direction cosine estimates, and thereby obtain highly accurate information on the radial direction of a source. Now, if we space the two vector sensors along a given axis much greater than a half-wavelength, there is longer a one-to-one correspondence between the phase of the ESPRIT eigenvalue and the direction cosine of the source relative to that axis. Yet, because of the larger aperture if we could determine which of the ambiguous angles was the correct one, it will be much more accurate than the angle estimate we would get from having the two vector sensors spaced by a half-wavelength.

This problem of determining which of the ambiguous angles is the correct one was initially solved by invoking the PRO-ESPRIT algorithm of the PI to extract from the generalized eigenvectors an estimate of the 6×1 E-H manifold at any of the three vector sensors. Again, once we have the 6×1 E-H manifold for a source, we may take the vector cross product between the top 3×1 subvector (electric field vector) with the bottom 3×1 subvector (magnetic field vector) to obtain an estimate of the radial direction of a source. The idea is to use this information to determine which of the ambiguous angles is the correct one.

That is, for a given source the eigenvalue information provided by ESPRIT yields a set of ambiguous u direction cosines (relative to the x -axis) and a set of ambiguous v direction cosines (relative to the y -axis). The eigenvector information from ESPRIT enables us to estimate the E-H manifold for a source which, in turn, gives us an estimate of a unit vector pointing in the radial direction of that source. We take its projection onto the x -axis, i.e., the x component, and select that member of the set of ambiguous u direction cosines closest to this projection. Similar processing of the two vector sensors spaced along the y -axis yields highly accurate v direction cosine estimates. Processing the outputs of all three vector sensors simultaneously, yielding 18×1 snapshot vectors, facilitates automatic pairing of the u and v estimates through the eigenvector information.

Simulations of the proposed scheme are presented in Figures 6 and 7 showing the variance of the u and v estimates decreasing dramatically as the inter-vector-sensor spacing increases up to a threshold point occurring at 30 wavelengths, for an SNR of 20 dB. The threshold is the inter-vector sensor spacing at which the performance departs dramatically from the Cramer-Rao Lower Bound. Simulations reveal this threshold to be SNR dependent. Dropping the SNR to 0 dB, lowers the threshold point to 5 wavelengths.

1.3.2 Rectangular Array of Arbitrary Number of Vector Sensors

The above concept was generalized for an arbitrary number of vector sensors regularly spaced on a rectangular grid, but with spacings much greater than a half-wavelength. In addition, an alternative procedure was developed for resolving the ambiguities. To this end, a generalized form of the MUSIC null spectrum was derived that only depended on u and v , not on the polarizations states. Thus, the concept is now to use the cross-product estimator obtained via PRO-ESPRIT to isolate a few candidate (u,v) grid points (rather than one), and then select the “correct” one based on which grid point yields

the lowest MUSIC null spectral value. Simulations of the new approach reveal the maximum allowable inter-vector sensor spacing to be much less dependent on the SNR than that realized with using only the cross-product estimator to resolve the ambiguities.

This work has been reported at a number of conferences and several full journal papers have either been submitted or are near completion. In addition, based on a conversation at the Adaptive Sensor Array Processing Workshop held at Lincoln Labs on 15 March 1994, Dr. Jeff Bull of Flam and Russel, Inc., called me for any reports or publications I had on this work. Dr. Bull is the holder of US Patent Number 5,300,885 issued 5 April 1994 for a "Field Probe for Measuring Vector Components of an Electromagnetic Field." This is the first electromagnetic vector sensor and was field tested by Dr. Gary Hatke at MIT Lincoln Laboratories.

In addition to the reports and conference papers I sent to Dr. Bull, I also sent him a set of slides on this work which he presented at a DF and Geolocation Conference sponsored by the Southwest Research Institute (in conjunction with the National Security Agency) in San Antonio, TX, on 6-7 June 1995. At that time, Dr. Bull had received a contract to do some work in vector sensor DF, although only for one vector sensor. However, Dr. Bull made use of my technique in dealing with a multipath application involving reflections off the ground.

We have also made a number of additional contributions in the area of vector sensor processing. First, we developed a closed-form underwater acoustic direction-finding scheme for use in conjunction with an arbitrarily spaced array of vector-hydrophones at unknown locations. Second, we developed an ESPRIT based algorithm for near-field and/or far-field azimuth & elevation angle estimation for use in conjunction with a single vector sensors. Third, we developed a novel MUSIC-based (MULTiple SIgnal Classification) blind source localization algorithm applicable to three-dimensional arbitrarily spaced arrays of velocity-hydrophone triads. These contributions are briefly expanded upon in the following sections.

1.3.3 Closed-Form Underwater Acoustic Direction-Finding With Arbitrarily Spaced Vector-Hydrophones at Unknown Locations

We have developed a novel ESPRIT-based, closed-form source localization algorithm applicable to arbitrarily spaced three-dimensional arrays of vector-hydrophones, whose locations need *not* be known. Each vector-hydrophone consists of two or three identical but orthogonally oriented velocity-hydrophones plus one pressure-hydrophone, all spatially co-located in a point-like geometry. A velocity-hydrophone measures one Cartesian component of the incident sonar wavefield's velocity-vector, whereas a pressure-hydrophone measures the acoustic wavefield's pressure. Velocity-hydrophone technology is well established in underwater acoustics and a great variety of commercial models have long been available. ESPRIT is realized by exploiting the non-spatial inter-relations among each vector-hydrophone's constituent hydrophones, such that ESPRIT's eigenvalues become independent of array geometry. Initial simulation results verify the efficacy and versatility of this innovative scheme.

Further, we developed a new and computationally efficient direction finding algorithm that (1) exploits the velocity vector-field information of impinging wavefronts (vs. the scalar wavefield model using only pressure-hydrophones), (2) estimates both elevation angles and azimuth angles, (3) requires rooting only two polynomials and no costly iterative searches. This work successfully adopts the

Root-MUSIC algorithm to L-shaped arrays of triads of co-located but orthogonally oriented velocity hydrophones. Each velocity hydrophone measures one Cartesian component of the acoustic velocity vector-wavefield. In one two-signal scenario, this new algorithm increases estimation accuracy by about 3-fold and lowers the resolution threshold by 25dB SNR relative to a pressure-hydrophone array of comparable hardware and software complexity.

1.3.4 Uni-Vector-Hydrophone ESPRIT for Near-Field/Far-Field Azimuth & Elevation Angle Estimation

We have developed a novel underwater acoustic eigenstructure (subspace) algorithm that yields closed-form direction-of-arrival (DOA) estimates using a single vector-hydrophone, which consists of three spatially co-located but orthogonally oriented velocity-hydrophones plus another optional co-located pressure-hydrophone. A vector-hydrophone thus measures all three Cartesian components of the underwater acoustic particle velocity vector-field plus the overall pressure scalar-field, thereby fully exploiting the acoustical particle velocity-field structure embedded in an underwater acoustical wavefield. *Uni-Vector-Hydrophone ESPRIT* is based on a matrix-pencil pair of temporally-displaced data sets collected from the single vector-hydrophone. Closed-form DOA estimates are obtained from the decoupled signal-subspace eigenvectors of the data correlation matrix via a subsequent normalization step. The algorithm under development requires no a priori knowledge of signal frequencies, suffers no frequency-DOA ambiguity, pairs automatically the x-axis direction-cosines with the y-axis direction-cosines, eliminates array inter-element calibration, can resolve up to three uncorrelated monochromatic sources impinging from the near-field or the far-field. It impressively out-performs an array of spatially displaced pressure-hydrophones of comparable array-manifold size and attendant computational load.

1.3.5 Self-Initiating MUSIC for Direction Finding in Underwater Acoustic Particle Velocity-Field Beamspace

We developed a novel MUSIC-based (MULTiple SIgnal Classification) blind source localization algorithm applicable to three-dimensional arbitrarily spaced arrays of velocity-hydrophone triads. The algorithm (1) self-generates coarse estimates of the sources' arrival angles to start off its MUSIC-based iterative search without any a priori source information, (2) exploits the sources' angular information embedded in the impinging underwater acoustic velocity-field, (3) automatically pairs the x-axis direction-cosine estimates with the y-axis direction-cosine estimates. This method uses spatially co-located but orthogonally oriented triads of velocity-hydrophones. Each velocity-hydrophone distinctly measures one Cartesian component the incident sonar wavefield's velocity-vector. The algorithm forms velocity-field beams at each velocity-hydrophone triad, and uses coarse estimates of each source's velocity-vector estimate obtained by decoupling the signal-subspace eigenvectors. Velocity-hydrophone technology is well established in underwater acoustics and a great variety of commercial models have long been available. Simulation results verify this innovative scheme's capability to self-generate initial direction-cosine estimates for its MUSIC-based iterative search and demonstrate the proposed algorithm's superior performance relative to a similarly spaced array of pressure-hydrophones. Under one scenario, the proposed method lowers the estimation bias by 95% and the estimation standard deviation by 47%, relative to a similarly configured array of pressure-hydrophones provided with a

priori initial arrival angle estimates.

2 PERSONNEL SUPPORTED

Faculty:	Michael D. Zoltowski (PI)
Postdoctoral Student:	Javier Ramos
Graduate Student:	Anand Kannan
Graduate Student:	Tai-Ann Chen

3 PUBLICATIONS

3.1 Peer-Reviewed Journal Articles Published and/or Accepted

1. J. Gansman, M. D. Zoltowski, and J. V. Krogmeier, "Multidimensional Multirate DOA Estimation in Beamspace," *IEEE Trans. on Signal Processing*, vol. 44, no. 11, Nov. 1996, pp. 2780-2792.
2. H. Liu and M. D. Zoltowski, "Blind Equalization in Antenna Array CDMA Systems," *IEEE Trans. on Signal Processing, Special Issue on Signal Processing for Advanced Digital Communications*, vol. 45, no. 1, Jan. 1997, pp. 161-172.
3. K. T. Wong and M. D. Zoltowski, "Closed-Form Underwater Acoustic Direction Finding with Arbitrarily Spaced Vector-Hydrophones at Unknown Locations," *IEEE Journal of Oceanic Engineering*, vol. 22, no. 4, July 1997, pp. 566-575.
4. J. Ramos, M. D. Zoltowski, and Hui Liu, "A Low Complexity Space-Time Processor for DS-CDMA Communications," *IEEE Signal Processing Letters*, September 1997, pp. 262-265.
5. K. T. Wong and M. D. Zoltowski, "Uni-Vector-Sensor ESPRIT for Multi-Source Azimuth-Elevation-Polarization Estimation," *IEEE Trans. on Antennas and Propagation*, vo. 45, no. 10, Oct. 1997, pp. 1467-1474.
6. K. T. Wong and M. D. Zoltowski, "Extended-Aperture Underwater Acoustic Multisource Azimuth/Elevation Direction-Finding Using Uniformly But Sparsely-Spaced Vector Hydrophones," *IEEE Journal of Oceanic Engineering*, vol. 22, no. 4, Oct. 1997, pp. 659-672.
7. K. T. Wong and M. D. Zoltowski, "Closed-Form Underwater Acoustic Direction-Finding with Arbitrarily Spaced Vector Hydrophones at Unknown Locations," *IEEE Journal of Oceanic Engineering*, vol. 22, no. 4, Oct. 1997, pp. 649-658.
8. C. Chatterjee, and V. Roychowdhury, J. Ramos, and M. D. Zoltowski, "Self-Organizing and Adaptive Algorithms for Generalized Eigen-Decomposition," *IEEE Trans. on Neural Networks*, vol. 8, no. 6, November 1997, pp. 1518-1530.
9. K. T. Wong and M. D. Zoltowski, "ESPRIT-Based Direction Finding Using A Sparse Rectangular Array with Dual-Size Spatial Invariances," scheduled to appear in, *IEEE Transactions on Aerospace and Electronic Systems*.

3.2 Peer-Reviewed Conference Papers Published

1. M. D. Zoltowski, "Blind Adaptive Beamforming for CDMA Based PCS/Cellular," (invited paper) *Conference Record of the 29th Asilomar IEEE Conference on Signals, Systems, and Computers*, 30 Oct.-1 Nov. 1995, pp. 378-382.
2. M. D. Zoltowski and A. S. Gecan, "Advanced Adaptive Null Steering Concepts for GPS," *Milcom '95*, 5-8 Nov. 1995, vol. 3, pp. 1214-1218.
3. A. S. Gecan and M. D. Zoltowski, "Power Minimization Techniques for GPS Null Steering Antennas," *Institute of Navigation (ION) Conference*, Palm Springs, CA, 13-15 Sept. 1995, *Winner of Best Paper Award in all of E-Systems for 1995*.
4. M. D. Zoltowski and J. Ramos, "Blind 2D RAKE Receivers Based on Space-Time MVDR Processing," *Proceedings IRSS '96: Interference Rejection and Signal Separation in Wireless Communications Symposium*, New Jersey Institute of Technology, Newark, NJ, 19 Mar. 1996, pp. 217-239.
5. J. Ramos and M. Zoltowski, "Optimum Filter for Blind Adaptive Beamformers Based on Baud Rate Knowledge," (invited paper) *Proceedings of the 1996 International Conference on Telecommunications*, (co-sponsored by IEEE and IEE), 13-17 April 1996, Istanbul, Turkey, pp. 423-426.
6. M. D. Zoltowski and J. Ramos, "Blind Multi-User Access Interference Cancellation for CDMA Based PCS/Cellular Using Antenna Arrays," *Proceedings of the 1996 IEEE Int'l Conference on Acoustics, Speech, and Signal Processing*, May 1996, Atlanta, GA, pp. 2730-2733.
7. K. T. Wong and M. Zoltowski, "Uni-Vector Sensor ESPRIT for Multi-Source Azimuth-Elevation Angle Estimation," *Digest of the 1996 IEEE Int'l Antennas and Propagation Symposium*, 21-26 July 1996, Balt., MD, pp. 1368-1371.
8. K. T. Wong and M. Zoltowski, "Diversely Polarized Root-MUSIC for Azimuth-Elevation Angle of Arrival Estimation," *Digest of the 1996 IEEE Int'l Antennas and Propagation Symposium*, 21-26 July 1996, Balt., MD, pp. 1352-1355.
9. K. T. Wong and M. Zoltowski, "Source Localization by 2-D Root-MUSIC with 'Scalar Triads' of Velocity Hydrophones," *Conference Record of the Midwest Symposium on Circuits and Systems*, 18-21 August 1996.
10. K. T. Wong and M. Zoltowski, "Sparse Array Aperture Extension with Dual-Size Spatial Invariances for ESPRIT-Based Direction Finding," *Conference Record of the Midwest Symposium on Circuits and Systems*, 18-21 August 1996.
11. K. T. Wong and M. Zoltowski, "Orthogonal Velocity-Hydrophone ESPRIT for Sonar Source Localization," *Proceedings of MTS/IEEE Oceans '96 Conference*, September 1996, pp. 1307-1312.

12. K. T. Wong and M. Zoltowski, "ESPRIT-Based Extended-Aperture Source Localization Using Velocity Hydrophones," *Proceedings of MTS/IEEE Oceans '96 Conference*, September 1996, pp. 1427-1432.
13. J. Ramos, M. Zoltowski, and M. Burgos, "Robust Blind Adaptive Array: A Prototype for GPS," *Digest of 1996 IEEE Int'l Symposium on Phased Array Systems and Technology*, 15-18 October 1996, Boston, MA, pp. 406-409.
14. T. F. Wong, T. M. Lok, J. S. Lehnert, and M. D. Zoltowski, "Spread-Spectrum Signaling Techniques With Antenna Arrays and Blind Adaptation," *Milcom '96*, McLean, VA, 21-24 Oct. 1996, pp. 194-198.
15. M. D. Zoltowski, Y.-F. Chen, and J. Ramos, "Blind 2D RAKE Receivers Based on Space-Time Adaptive MVDR Processing for the IS-95 CDMA System," *Milcom '96*, McLean, VA, 21-24 Oct. 1996, pp. 618-622.
16. M. D. Zoltowski and J. Ramos, "Blind Interference Cancellation and Optimal Multipath Combining for Direct Sequence Spread Spectrum Communications Using Antenna Arrays," *Space Technology & Applications International Forum (STAIF-97)*, 26-30 January 1997, Albuquerque, NM, pp. 963-968.
17. T. A. Thomas and M. D. Zoltowski, "Nonparametric Interference Cancellation and Equalization for Narrowband TDMA Communications Via Space-Time Processing," *IEEE Signal Processing Advance in Wireless Communications Workshop - SPAWC '97*, Paris, France, 16-18 April 1997, pp. 185-188.
18. J. Ramos and M. D. Zoltowski, "Blind Space-Time Processor for CDMA Cellular Systems for SINR Maximization," *IEEE Signal Processing Advance in Wireless Communications Workshop - SPAWC '97*, Paris, France, 16-18 April 1997, pp. 273-276.
19. T. A. Thomas and M. D. Zoltowski, "Novel Receiver Signal Processing for Interference Cancellation and Equalization in Cellular TDMA Communications," *Proc. of the 1997 IEEE Int'l Conf. on Acoustics, Speech, and Signal Processing*, 21-24 April 1997, Munich, Germany, pp. 3881-3884.
20. J. Ramos and M. D. Zoltowski, "Blind 2D RAKE Receiver for CDMA Incorporating Code Synchronization and Multipath Time Delay Estimation," *Proc. of the 1997 IEEE Int'l Conf. on Acoustics, Speech, and Signal Processing*, 21-24 April 1997, Munich, Germany, pp. 4025-4029.
21. K. T. Wong and M. D. Zoltowski, "Closed-Form Multidimensional Multiple Invariance ESPRIT," *Proc. of the 1997 IEEE Int'l Conf. on Acoustics, Speech, and Signal Processing*, 21-24 April 1997, Munich, Germany, pp. 3489-3492.
22. T. A. Thomas and M. D. Zoltowski, "Novel Receiver Space-Time Processing for Interference Cancellation and Equalization in Narrowband TDMA Communications," *Proceedings of IEEE Vehicular Technology Conference (VTC) '97*, Phoenix, AZ, 4-7 May 1997, pp. 160-164.

23. K. T. Wong and M. D. Zoltowski, "Extended Aperture Spatial Diversity & Polarization Diversity Using a Sparse Array of Electric Dipoles or Magnetic Loops," *Proceedings of IEEE Vehicular Technology Conference (VTC) '97*, Phoenix, AZ, 4-7 May 1997, pp. 1163-1167.
24. M. D. Zoltowski and A. Kannan, "Blind Separation of Co-Channel Digital Signals Under Imperfect Carrier Recovery," *Proceedings of Milcom '97*, Monterey, CA, Vol. 2, pp. 832-835, 2-5 Nov. 1997.
25. K. T. Wong and M. D. Zoltowski, "Sparse Array Spatial Diversity with Dual-Size Spatial Invariance to Mitigate Fading-Channel Effects," *Proceedings of IEEE Int'l Conference on Communications (ICC) '97*, Montreal, Canada, 8-12 June 1997.
26. M. D. Zoltowski and D. Tseng, "Blind Channel Identification for Narrowband Digital Communications Based on Parametric Modelling of the Channel Impulse Response," (*invited paper*) *Proceedings 35th Annual Allerton Conference on Communications, Systems, and Computing*, 29 Sept.-1 Oct., 1997, pp. 503-512.
27. M. D. Zoltowski and D. Tseng, "On The Use of Basis Functions in Blind Equalization Based on Deterministic Least Squares," *invited paper, Conf. Record of the 31st Asilomar IEEE Conference on Signals, Systems, and Computers*, vol. 1, pp. 816-822, 30 Oct.-1 Nov. 1997.
28. K. T. Wong and M. D. Zoltowski, "Polarization Beamspace Self-Initiating MUSIC for Azimuth/Elevation Angle Estimation" *IEE RADAR'97*, Edinburgh, UK, 14-16 October 1997.

3.3 Submitted Peer-Reviewed Journal Articles

1. M. D. Zoltowski, J. Ramos, C. Chatterjee, and V. Roychowdhury, "Blind Adaptive 2D RAKE Receiver for DS-CDMA Based on Space-Frequency MVDR Processing," accepted subject to major revisions, *IEEE Trans. on Signal Processing*, reviews received 20 February 1997.
2. K. T. Wong and M. D. Zoltowski, "Colocated-Orthogonal-Hydrophone ESPRIT for Sonar Azimuth-Elevation Source Localization," submitted to *IEE Proceedings - Part F: Radar, Sonar and Sound Navigation*, 15 March 1996.
3. K. T. Wong and M. D. Zoltowski, "Azimuth & Elevation Angle Estimation with Self-Initiating MUSIC in Polarized Beamspace," submitted to *IEE Proceedings - Part F: Radar, Sonar, and Navigation*, 28 March 1996. Reviews received 15 July 1997. Revised and resubmitted.
4. M. D. Zoltowski and K. T. Wong, "High-Accuracy 2D Angle Estimation with Extended Aperture Vector-Sensor Arrays," submitted to *IEEE Transactions on Signal Processing*, 1 July 1997.

4 INTERACTIONS/TRANSITIONS: 1 July 1995 - 31 July 1996

4.1 A. Participation/presentations at meetings, conferences, seminars, etc

- Attended the *29th Asilomar IEEE Conference on Signals, Systems, and Computers*, held 0 Oct.-1 Nov. 1995 in Pacific Grove, CA. At this conference, I performed the following functions:

- presented two technical papers
 - Organized and chaired Special Session entitled “Smart Antenna Arrays for Wireless Communications” on 1 Nov. 1995
- Presented an invited paper at *IRSS '96: Interference Rejection and Signal Separation in Wireless Communications Symposium*, New Jersey Institute of Technology, Newark, NJ, on 19 Mar. 1996.
- Attended the *1996 IEEE Int'l Conference on Acoustics, Speech, and Signal Processing* held 8-12 May 1996 in Atlanta, Georgia. At this conference, I performed the following functions:
 - presented three technical papers (see Section 3.2)
 - chaired lecture session entitled “Adaptive Beamforming” on 9 May 1996
 - attended the meeting of the Editorial Board of the IEEE Signal Processing Society (currently serve as an associate editor for the IEEE Transactions on Signal Processing)
 - attended a meeting of the Statistical Signal and Array Processing Technical Committee of the IEEE Signal Processing Society (elected May 1995 for three year term)
 - attended a meeting of the Chapter Chairs of the IEEE Signal Processing Society (elected Chapter Chair of Central Indiana Sect. of IEEE, May 1995 for two year term)

4.2 Consultative and advisory functions to other laboratories and agencies, especially Air Force and other DoD laboratories

- Participated in the DISA/AFOSR/Rome Lab Technical Exchange held 12 October 1995 at the Defense Information Systems Agency, Center for Systems Engineering, Parkridge III, Reston, VA. I was invited by my AFOSR program manager, Dr. Jon Sjogren, to attend and give a 20 minute overview of my work on space-time adaptive processing for wireless communications.
- Served as a consultant to Dr. James B. Tsui, WL/AAWP-1 HNGR 4B, Wright Patterson Air Force Base (WPAFB), Dayton, OH 45433, 1-513-255-6133, on issues related to GPS receivers and smart antenna array processing for wireless communications on 16 June 1996. Dr. Tsui visited with myself and the post-doctoral assistant supported by the grant, Dr. Javier Ramos, for the day on 16 June 1996.

4.3 Transitions

Enabling research: vector sensor array processing for high-resolution DF
 Company: Flam and Russel, Inc., Horsham, PA
 Point of Contact: Dr. Jeffrey Bull
 e-mail: jbull@agrp.com

Dr. Bull of Flam and Russel, Inc. was the inventor of the SuperCART array. He is the holder of US Patent Number 5,300,885 issued 5 April 1994 for a “Field Probe for Measuring Vector Components of an Electromagnetic Field.” This is the first electromagnetic vector sensor and was field tested by Dr. Gary Hatke at MIT Lincoln Laboratories. Based on a conversation at the Adaptive Sensor Array Processing Workshop held at Lincoln Labs on 15 March 1994, Dr. Bull called me for any reports or

publications I had on my extended aperture vector sensor array work. I also sent him a set of slides on this work which he presented at a DF and Geolocation Conference sponsored by the Southwest Research Institute (in conjunction with the National Security Agency) in San Antonio, TX, on 6-7 June 1995. At that time, Dr. Bull had received a contract to do some work in vector sensor DF.

5 INTERACTIONS/TRANSITIONS: 1 August 1996 to 31 Jul 1997

5.1 A. Participation/presentations at meetings, conferences, seminars, etc

- Attended and presented an invited technical paper (invited by Dr. Scott Goldstein) at *IEEE Milcom '96* held 21-24 Oct. 1996 in McLean, VA (see Section 3.2).
- Attended *Space Technology & Applications International Forum (STAIF-97)* held 26-30 January 1997 in Albuquerque, NM. At this conference, I performed the following functions:
 - presented one technical paper (see Section 3.2)
 - Co-organized with Dr. Jon Sjogren a Special Session entitled “Connecting to the Infosphere: Communications Technology for the Future Warfighter,” on 30 January 1997.
- Attended and presented two technical papers at *IEEE Signal Processing Advance in Wireless Communications Workshop - SPAWC '97*, Paris, France on 16-18 April 1997 (see Sect. 3.2).
- Attended the *1997 IEEE Int'l Conf. on Acoustics, Speech, and Signal Processing* held in Munich, Germany on 21-24 April 1997. At this conference, I performed the following functions:
 - presented an *Expert Summary* on Array Processing – one of 8 researchers invited to present an *Expert Summary* at ICASSP '97.
 - reviewed 50 submitted paper summaries a-priori.
 - presented three technical papers.
 - chaired lecture session entitled “Array Processing III: Wireless Communications.”
 - attended the meeting of the Editorial Board of the IEEE Signal Processing Society (currently serve as an associate editor for the IEEE Transactions on Signal Processing.)
 - attended a meeting of the Statistical Signal and Array Processing Technical Committee of the IEEE Signal Processing Society (elected May 1995 for three year term)
 - attended a meeting of the Chapter Chairs of the IEEE Signal Processing Society (elected Chapter Chair of Central Indiana Sect. of IEEE, May 1995 for two year term)
 - attended a meeting of Education Committee of the IEEE Signal Processing Society of IEEE (appointed by SSAP TC Chair as liason).
- Attended and presented a technical paper at *IEEE Vehicular Technology Conference (VTC) '97* held in Phoenix, AZ on 4-7 May 1997 (see Section 3.2).

5.1.1 Invited Seminars.

- “Space-Time Processing for Interference Cancellation and Equalization in Narrowband Digital Communications,” (*invited by Prof. Ubli Mitra*) SPANN Seminar Series, Department of Electrical and Computer Engineering, Ohio State University, Columbus, OH, 7 October 1996.
- “Space-Time Processing for Interference Cancellation and Equalization in Narrowband Digital Communications,” (*invited by Prof. Athina Petropulu*) Distinguished Lecturer Series, Department of Electrical and Computer Engineering, Drexel University, Phila., PA, 25 November 1996.
- “Space-Time Processing for DS-CDMA: Blind Adaptive 2D RAKE Receiver” and “Space-Time Processing for TDMA: Nonparametric Multichannel Equalization and Interference Cancellation” (*invited by Dr. Fred Vook*) Communications Systems Research Lab, Motorola, Schaumburg, IL, 12 March 1997.

5.2 B. Consultative and advisory functions to other laboratories and agencies, especially Air Force and other DoD laboratories

- Participated in a Future Research Directions in Signal Processing Panel held in Durango, CO, 1-4 Aug. 1996. The four day workshop was sponsored by the Signal Processing Systems Program of the MIPS Division, CISE Directorate of the National Science Foundation. I was invited by the Program Director, Dr. John Cozzens, to participate in discussions leading to recommendations on research areas for emphasis and de-emphasis in future signal processing funding.
- Served on review panel for Professional Opportunities for Women in Research and Education (POWRE) Award Program, CISE Directorate, MIPS, Signal Processing Systems Program, Arlington, VA, 12 August 1997.

6 INTERACTIONS/TRANSITIONS: 1August 1997 - 31 May 1998

6.1 A. Participation/presentations at meetings, conferences, seminars, etc

- Attended the *1998 IEEE Int'l Conf. on Acoustics, Speech, and Signal Processing* held during 12-15 May 1998 in Seattle, WA. At this conference, I performed the following functions:
 - presented two technical papers.
 - chaired poster session: “Array Processing III: Adaptive Beamforming and Applications.”
 - attended a meeting of the Communications Technical Committee as an elected member
 - attended a meeting of Education Committee of the IEEE Signal Processing Society of IEEE
 - attended a meeting of the Board of Governors of the IEEE Signal Processing Society of IEEE (elected Secretary of EEE SP Society for 3 year term commencing 1 Jan. 1999.)
- Student supported by grant presented a technical paper at *IEEE Vehicular Technology Conference (VTC) '97* held in Ottawa, Ontario, Canada during 18-21 May 1998

6.1.1 Invited Seminars.

- “Space-Time Signal Processing for Wireless Communications: Equalization and Interference Cancellation,” ECE Dept. Colloquium at University of Minnesota (televised), (*invited by Prof. Ahmed Tewfik*) 12 February 1998.
- “Smart Antennas for Wireless Communications,” (*invited by Prof. Mani Venkata*) Jerry Junkins Endowed Chair Seminar Series, Department of Electrical and Computer Engineering, Iowa State University, Ames, IA, 13 February 1996.

6.2 B. Consultative and advisory functions to other laboratories and agencies, especially Air Force and other DoD laboratories

- Served on review panel for Professional Opportunities for Women in Research and Education (POWRE) Award Program, CISE Directorate, MIPS, Signal Processing Systems Program, Arlington, VA, 12 August 1997.

6.3 C. Transitions

We will continue our dialogue with Dr. James Tsui at Wright Laboratories on the Wright-Patterson Air Force Base in Dayton, OH to work towards a transition of this research. Dr. Tsui is currently overseeing the development of an experimental multichannel receiver for GPS at Wright Labs.

7 NEW DISCOVERIES, INVENTIONS, PATENT DISCLOSURES

None.

8 HONORS/AWARDS

- *E-Systems Best Paper Award for 1995* for A. S. Gecan and M. D. Zoltowski, “Power Minimization Techniques for GPS Null Steering Antennas,” *Institute of Navigation (ION) Conference*, Palm Springs, CA, 13-15 Sept. 1995.
- Post-Doctoral student, J. Ramos, supported by the grant was awarded *Best PhD Dissertation in Electrical Engineering by the Spanish Professional Association of Engineers*, 1995-1996. Dr. Ramos’ dissertation, “Novel Techniques for Processing Digital Arrays,” Polytechnic University of Madrid, was co-advised by the PI with Dr. Mateo Burgos.
- Presented *Expert Summary on Array Processing* at IEEE ICASSP ’97 in Munich, Germany, on 24 April 1997. One of 8 researchers invited to present an *Expert Summary* by organizing committee of IEEE ICASSP ’97.
- Board of Governors, Member-at-Large, elected November 1997 for three year term.
- Secretary of IEEE Signal Processing Society, elected 16 May 1998 by Board of Governors, for a three year term starting January 1999.

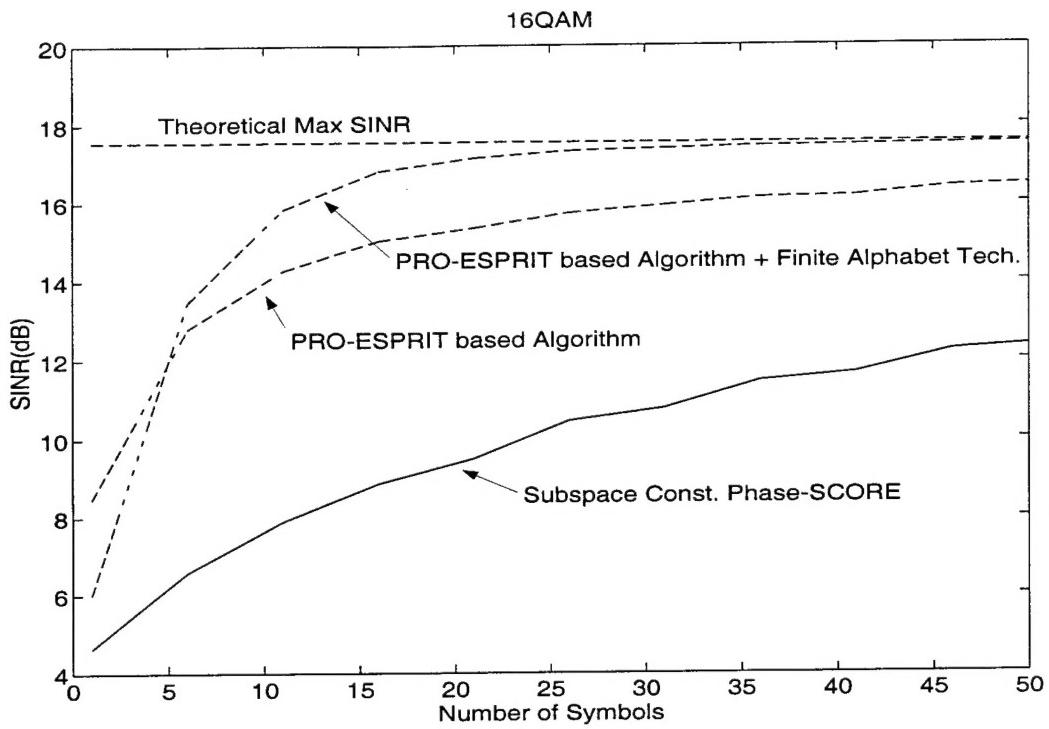


Figure 1: Convergence Speed of New Blind Beamformer: 16-QAM Modulation

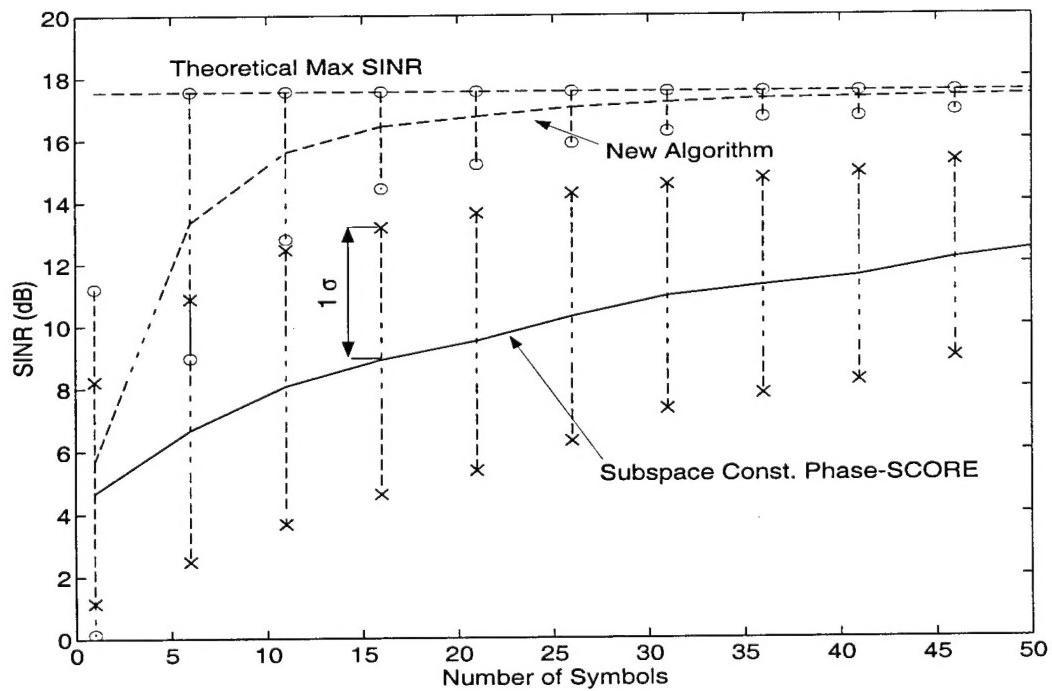


Figure 2: Convergence Speed: Mean Output SINR plus Std. Dev. for 16-QAM

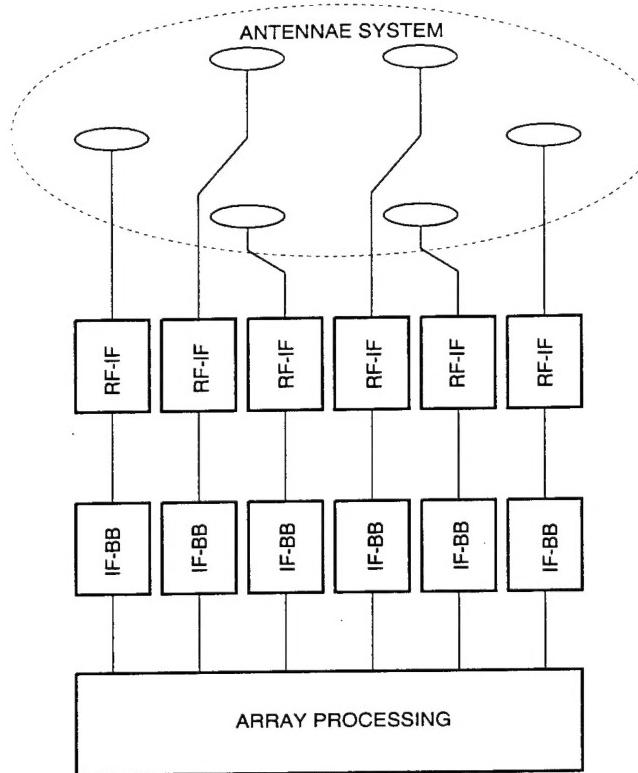


Figure 3. Block diagram of the prototype.

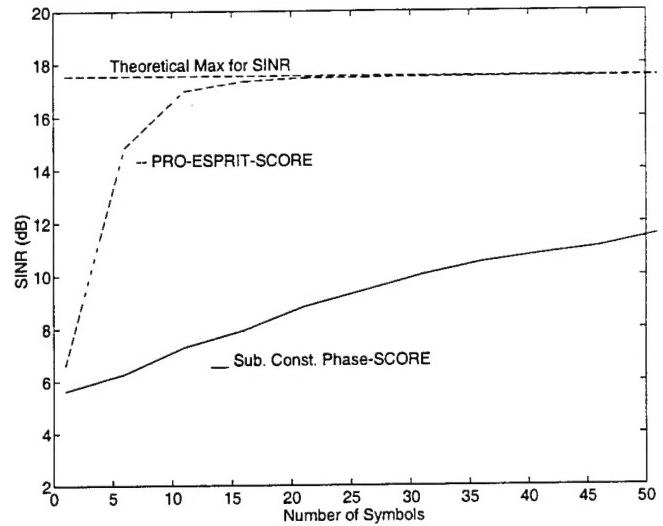


Figure 4. Convergence speed of the Adaptive Algorithm.

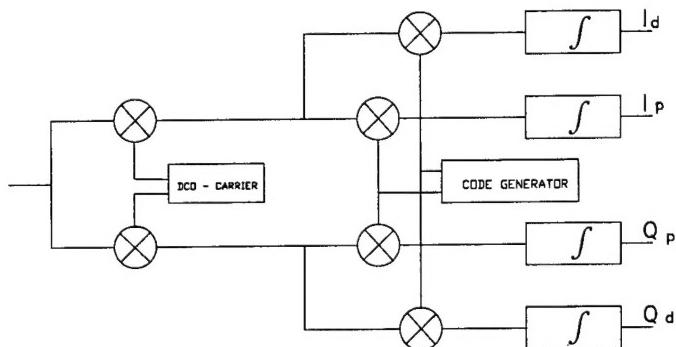


Figure 5. Structure of IF-BB Stage.

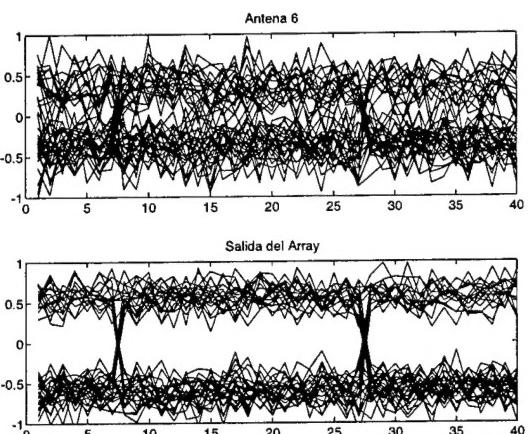


Figure 6. Eye diagram at one of the antennae and at the output of the array processing.

Figure 7: RMS standard deviation of $\{\hat{u}_1, \hat{v}_1, \hat{u}_2, \hat{v}_2\}$ vs. inter-sensor spacing: 3×3 rectangular vector sensor array, $\theta_1 = 80^\circ, \phi_1 = 30^\circ, \gamma_1 = 45^\circ, \eta_1 = -90^\circ, \mathcal{P}_1 = 1, \theta_2 = 75^\circ, \phi_2 = 35^\circ, \gamma_2 = 45^\circ, \eta_2 = 90^\circ, \mathcal{P}_2 = 1$, AWGN at 20dB, 50 snapshots per experiment, 300 independent experiments.

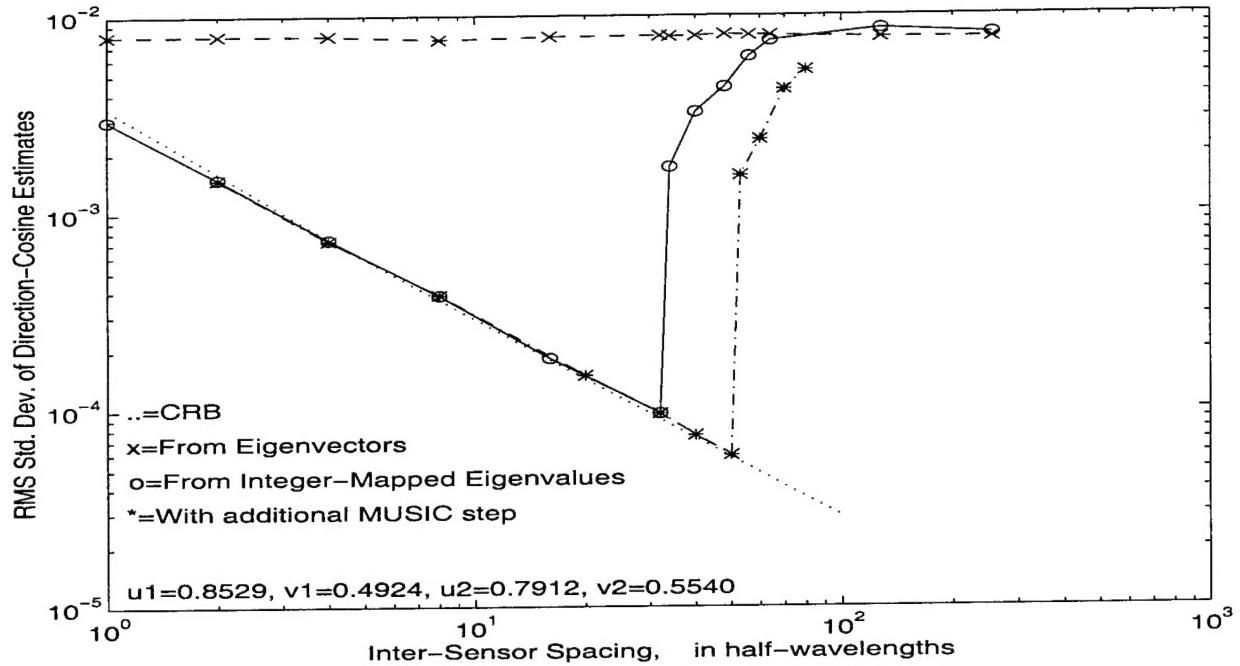
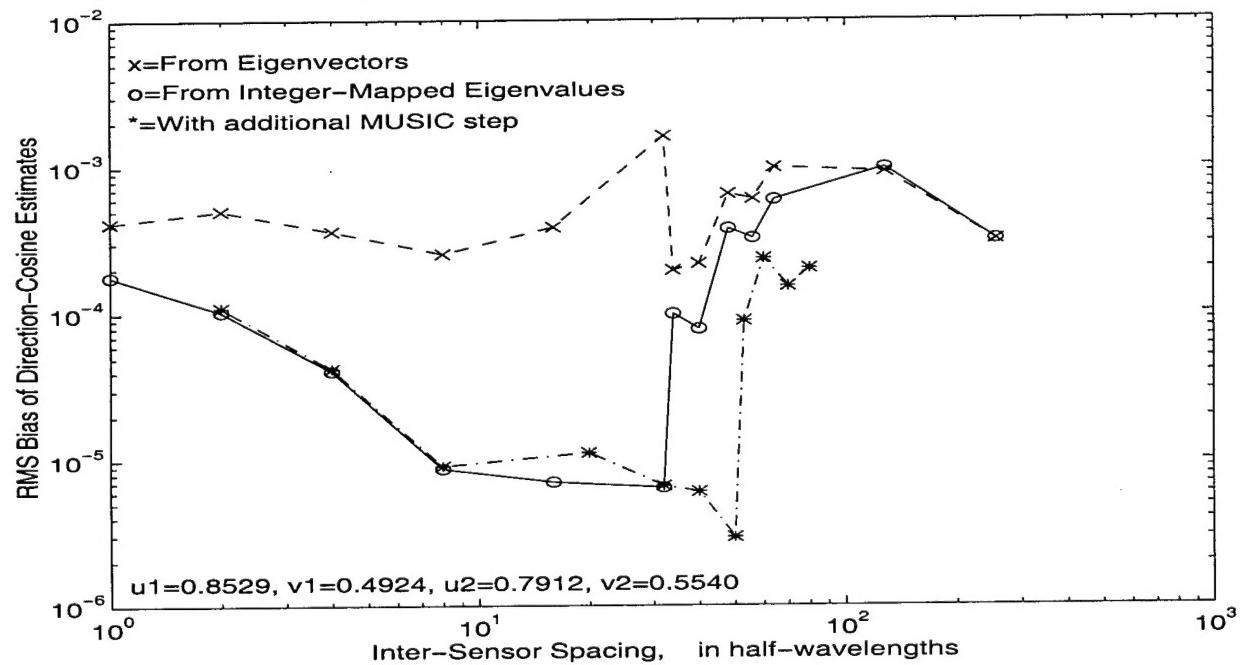


Figure 8: RMS bias of $\{\hat{u}_1, \hat{v}_1, \hat{u}_2, \hat{v}_2\}$ vs. inter-sensor spacing: same settings as in Figure 1.



Approved for public release;
distribution unlimited.

AIR FORCE SCIENTIFIC RESEARCH (AFSC)
NOTICE OF PUBLIC RELEASE
This document has been reviewed and is
approved for public release under AFN AFR 190-12
Distribution unlimited
Joan Boggs
STINFO Program Manager